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Avoiding Disasters: Strengthening Societal Resilience to Natural Hazards

Changing Weather Extremes Call for Early Warning of Potential for Catastrophic Fire

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Key Points:

- Altered frequencies of extreme weather events may affect the incidence, seasonality, severity and impacts of forest fires globally
- Forests in disparate environments switch to a state of critical flammability at similar levels of fine dead fuel moisture content within days
- Dead fuel moisture content can be reliably predicted from gridded weather data, providing early warning of changes in forest flammability

Supporting Information:

- Supporting Information S1

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Abstract Changing frequencies of extreme weather events and shifting fire seasons call for enhanced capability to forecast where and when forested landscapes switch from a nonflammable (i.e., wet fuel) state to the highly flammable (i.e., dry fuel) state required for catastrophic forest fires. Current forest fire danger indices used in Europe, North America, and Australia rate potential fire behavior by combining numerical indices of fuel moisture content, potential rate of fire spread, and fire intensity. These numerical rating systems lack the physical basis required to reliably quantify forest flammability outside the environments of their development or under novel climate conditions. Here, we argue that exceedance of critical forest flammability thresholds is a prerequisite for major forest fires and therefore early warning systems should be based on a reliable prediction of fuel moisture content plus a regionally calibrated model of how forest fire activity responds to variation in fuel moisture content. We demonstrate the potential of this approach through a case study in Portugal. We use a physically based fuel moisture model with historical weather and fire records to identify critical fuel moisture thresholds for forest fire activity and then show that the catastrophic June 2017 forest fires in central Portugal erupted shortly after fuels in the region dried out to historically unprecedented levels.

1. Forest Fire Hazard Prediction for Risk Mitigation

Forest fires are a reoccurring hazard of forested landscapes globally, posing significant risks to local and regional communities, which are projected to increase under future climate conditions (Bowman et al., 2017; Moritz et al., 2014). The intrinsic fire hazard present in forested landscapes during the warmer/drier seasons (Hardy, 2005) is generally acknowledged and routinely prepared for by communities and government agencies. However, most countries lack a reliable early warning system capable of detecting or forecasting where and when forests will switch to critical forest flammability levels, which is determined largely by the moisture content of fine dead surface fuels (e.g., fine litter; Fernandes & Cruz, 2012; Gill & Zylstra, 2005; Zylstra et al., 2016). At the landscape scale, potential for large fires is highly dependent on the spatial connectivity of dry fuel areas (Bradstock et al., 2009; Caccamo et al., 2012). Therefore, early warning of potential for landscape-scale fire requires at least two components: (1) a reliable, spatially explicit prediction of fine dead fuel moisture content and (2) objective criteria for the interpretation of predicted fuel moisture patterns in terms of potential for a major landscape fire.

Existing operational fire danger indices such as the Canadian Forest Fire Weather Index (FWI; Van Wagner, 1987) or the Australian McArthur Forest Fire Danger Index (FFDI; McArthur, 1967) are numerical ratings of potential fire behavior calculated from daily temperature, relative humidity, wind speed and rainfall (Dowdy et al., 2009). Both FWI and FFDI combine indices of fuel dryness and surface soil moisture with indices of fire spread rate and/or fire intensity to produce an index of fire danger with an abstract scale from low to catastrophic. Identifying forest areas that are approaching or exceeding critical flammability levels conducive of major landscape fire on the basis of FWI or FFDI is inherently problematic. First, the fuel dryness and soil moisture indices within FWI and FFDI are highly simplified models of the wetting and drying of fine dead fuels or surface soil that tend to perform poorly as predictors of actual moisture content (e.g., Aguado et al., 2007; Schunk et al., 2017; Soler Martin et al., 2017; Vinodkumar et al., 2017; Wotton & Beverly, 2007). Second, studies relating fire danger indices such as FWI or FFDI, or the embedded fuel moisture indices, to quantitative measures of fire activity, such as burned area (BA), typically yield mixed results. For example, in a global study Bedia et al. (2015) found FWI to be weakly correlated with fire season BA in much of the world, including the Iberian Peninsula, while Urbieta et al. (2015) found strong positive relationships between BA and fire season FWI in several subregions of the European Mediterranean, including much of Spain, but weak to moderate correlations for national forests in the Pacific West of the United States (California, Oregon). Flannigan et al. (2005) found mean FWI, or the mean daily severity rating (DSR, an exponential function of FWI), to explain 36%–56% of interannual variation in BA in four of eight Canadian ecozones. Abatzoglou and Kolden (2013) found the fine fuel moisture code (FFMC), which is embedded within the FWI, to explain 54% of fire season BA in forest environments of Northern California, but no generic model for the western United States. Nogueira et al. (2017) report moderate to strong correlations between several fire danger indices, including FWI and FFDI, and monthly BA for four biomes in Brazil. Tian et al. (2011) however, found that FWI, or the FFMC, explained only a small fraction of variation in BA in forests of the Daxing'anling region of northern China. Clearly, there is substantial regional variation in the response of BA or other fire activity metrics to the common fire danger indices, potentially causing confusion and uncertainty among fire management agencies and the public about the practical meaning of the different fire danger categories.

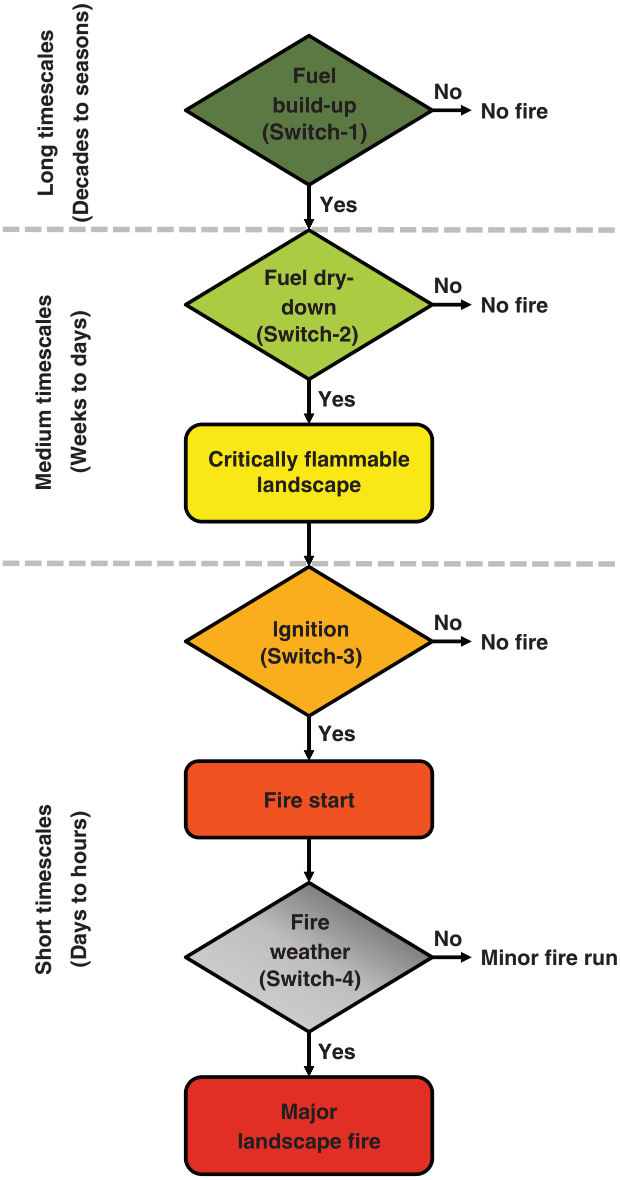

Figure 1. Occurrence of major forest fires is controlled by a hierarchy of four environmental constraints, or switches connected in series, that operate at different time scales. For a forest fire to start there must be sufficient fuel to facilitate fire propagation (Switch 1), the fuel must be dry enough to burn (Switch 2) and there must be an ignition (Switch 3). Once a fire has started its behavior and likelihood of developing into a major fire is largely controlled by the weather (Switch 4), in particular air temperature, relative humidity, and wind speed.

We argue that early warning systems of forest fire danger should commence with a physically based rating of the flammability of fuels, because this controls the likelihood of a fire starting, and that does not depend on individual-site calibrations which would limit its wide applicability. Rating the potential behavior of fires could then be done only where flammability thresholds are exceeded (Figure 1), in line with the sequential nature of conditions and events leading to major forest fires (San-Miguel-Ayanz et al., 2013). Early detection or forecasts of where and when forested landscapes approach critical flammability thresholds would help fire management and emergency agencies to more strategically deploy resources to high risk areas and prepare for potential evacuations or other risk mitigation measures.

Here, we demonstrate that the key building blocks for operational monitoring and forecasting of forest flammability already exist (Nolan et al., 2016a, 2016b; Resco de Dios et al., 2015). We apply this methodology to demonstrate that the severe forest fires of 17–22 June 2017 in central Portugal, near the town of Pedrogão Grande, erupted when the predicted moisture content of forest fuels in the area and across much of the country's forest regions exceeded critical thresholds for major fire activity (Figure 2). Despite the catastrophic nature of these forest fires, the FWI reportedly failed to provide early warning of the extreme fire danger experienced during the days of the fires. For instance, according to the Portuguese Institute for Sea and Atmosphere (Instituto Português do Mar e da Atmosfera [IPMA], 2017), on 17 June 2017, FWI values at the weather stations surrounding Pedrogão Grande ranged between the 66th and 92nd percentile of fire season values, with four of five stations within 44 km distance from the fires failing to record FWI in the extreme category (Table S1, Supporting Information S1). Similarly, gridded FWI forecasts for 17–19 June 2017 issued by the European Forest Fire Information System (EFFIS) at the Joint Research Centre (http://effis.jrc.ec.europa.eu/static/effis_current_situation/public/index.html) were also not capturing the extreme conditions under which the fires were burning.

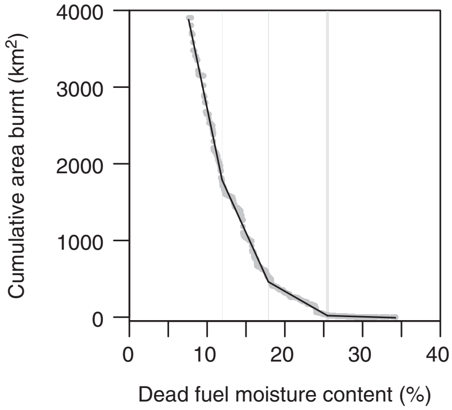

Figure 2. Relationship between cumulative area burnt by forest fire in Portugal (2001–2015) and predicted fine dead fuel moisture content. Thresholds in fuel moisture associated with major increases in fire activity (26%, 18%, 12%) were determined by fitting linear regressions to either side of break-points in the data as in previous analyses (Nolan et al., 2016b). The vertical gray bars represent the 95% confidence interval (CI) of critical fuel moisture thresholds. The r^2 for the segmented regression is 0.97.

2. Fuel Moisture—The on/off Switch for Forest Flammability

Forest fire is a complex stochastic phenomenon controlled by four principal environmental constraints, or "switches," operating at disparate timescales (Boer et al., 2016; Bradstock, 2010) (Figure 1). Forest fires burn a combination of live and dead plant material (i.e., fuel). First, fire requires accumulation of fuels to a level that facilitates fire propagation (Switch 1, Figure 1). Second, the fuels must dry out to become ignitable and combustible (Switch 2); once those conditions are met the landscape is in a flammable state and fires will readily start with an ignition (Switch 3), and spread depending on fire weather conditions (Switch 4).

Here, we focus on forest flammability, which is a function of the interactions of fuel amounts and their availability to burn. Fuel accumulation operates at timescales of decades to seasons, depending on vegetation type and climate, while the drying of fuels can take weeks to days (Nolan et al., 2016b). The moisture content of fine dead fuel material such as dead leaves and twigs equilibrates relatively quickly (less than day) with atmospheric moisture, while coarser fuel material such as branches and logs takes longer to respond (days to weeks). As fine fuel material ignites more readily, assessments of forest flammability should focus on the moisture content of fast-responding, fine dead fuels (Gill & Zylstra, 2005).

Whenever fuels are sufficiently abundant, spatially continuous, and dry enough to sustain fire, the landscape is essentially in an "armed" state as any ignition on a hot windy day will trigger a spreading fire (Figure 1). In most forests, dead fuel material, in the form of leaf litter, dead branches and logs, is continually present in enough abundance to sustain a fire so that the switching to this armed state of critical forest flammability is effectively controlled by the fluctuating moisture content of the fuels (Boer et al., 2016; Bradstock, 2010). Daily variation in the moisture content of fine dead fuels (FM) can be reliably predicted and mapped at subcontinental scale from gridded estimates of vapor pressure deficit (D) (Resco de Dios et al., 2015). D is calculated from standard weather observations or can be predicted from remotely sensed land surface temperature, providing the basis for spatially explicit prediction of fine dead fuel moisture (Nolan et al., 2016a); in the remainder referred to as FM_D. Importantly, as shown previously for temperate forests in Australia, daily FM_D is a strong predictor of fire activity level (Nolan et al., 2016b).

3. Central Portugal's Record Fuel Dryness of June 2017

In Portugal, large forest fires (>100 ha) occur in most years (Carvalho et al., 2008; Marques et al., 2011). To determine how fire activity is affected by fuel dryness, we analyzed historical forest fire records for Portugal for the period 2001–2015 (ICNF, 2017) together with "hindcasted" daily FM_D to identify FM_D thresholds that distinguish different categories of forest flammability. Following Nolan et al. (2016a) a data set of gridded daily vapor pressure deficit at 0.01° × 0.01° resolution was created for mainland Portugal from interpolated weather station records (Sistema Nacional de Informação de Recursos Hidricos [SNIRH], 2017) of mean daily air temperature and relative humidity, and then used to predict daily FM_D as a function of vapor pressure deficit (D):

$$FM_D = FM_0 + FM_1 e^{-mD} \tag{1}$$

where FM_0, FM_1 and m are fitting parameters. FM_0 represents the minimum fuel moisture content (%), $FM_0 + FM_1$ is the fuel moisture content when D is zero, and m is the rate of change in fuel moisture content with D (kPa). Model calibration and validation have been described in detail elsewhere (Nolan et al., 2016a). In summary, the model was calibrated using measurements at the Cumberland Plain Ozflux site, a temperate *Eucalpytus* woodland 60 km west from Sydney, and validated using data from 16 forest sites across a ~1000 km gradient in SE Australia and two additional Fluxnet sites in California (Goulden et al., 2012). Data for model validation spans across marked gradients of precipitation (129–1404 mm yr^{-1}) and of leaf area index (0.1–5.8 m^2 m^{-2}) and, given the good fit to actual fuel moisture data, the authors concluded that the model was of broad application and did not require site-specific calibration. The model parameter values proposed in Nolan et al. (2016a) where 6.79, 27.43, and 1.05 for FM_0, FM_1, and m, respectively, and the interested reader may consult further details in the original publication. Matching fire locations and dates with spatially explicit FM_D, we then calculated the cumulative area burnt by forest fire as a function of declining FM_D, following Dennison and Moritz (2009). Breakpoints in the relationship between cumulative BA and FM_D (Figure 2), objectively identified using segmented regression, are indicative of dynamic transformations in the flammability of the landscape as dry fuel areas become increasingly connected (Caccamo et al., 2012; Nolan et al., 2016b).

Our analysis confirms that FM_D is a strong determinant of the area burnt by forest fires in Portugal (Figure 2). Hardly any forest area burnt when FM_D exceeded 26%, which is consistent with reported moisture contents of extinction of 25%–35% for woody fuels (Burgan & Rothermel, 1984; Fernandes et al., 2008; Rothermel, 1972). Pronounced increments in the area burnt occurred when FM_D dropped below 18% and increased further when FM_D fell below 12% (Figure 2). The vast majority (87%) of the total BA in the 2001–2015 period occurred when FM_D was 18% or below. Significantly, the fuel moisture threshold needed to trigger high frequency of large fires in Portuguese forests (12%) is very close to the large-fire, fuel moisture thresholds found for eucalypt forests of southeast Australia (12.4%–15.1%) (Nolan et al., 2016b) and boreal and subalpine forests in Alberta and Saskatchewan, Canada (14%) (Nash & Johnson, 1996). These fuel moisture thresholds are also consistent with observations in southwestern U.S. forests that showed a sharp increase in BA when vapor pressure deficit is in the 1.3–1.4 kPa range (Williams et al., 2015), which would correspond to FM_D of 13%–14% according to our FM_D model. The similarity of these fuel moisture thresholds suggests that physically based estimation of dead fuel moisture content provides a sound basis for the detection and forecasting of critical flammability conditions in a wide range of forest environments.

In May 2017, FM_D in the Pedrogão Grande area of central Portugal fluctuated within the 15%–30% range and then decreased rapidly from early June as extreme heat built up over the interior of the Iberian Peninsula (Figure 3). By 9 June 2017, the median FM_D in the Pedrogão Grande area was approximately 20% and dropped below 18% by 14 June 2017, leaving the landscape in a highly flammable state. On 17 June 2017 when the Pedrogão Grande fires started the median FM_D in the area was below the 12% threshold. Conditions of extreme forest flammability continued in the Pedrogão Grande area for three consecutive days in which catastrophic fires claimed 64 lives and injured many more, before FM_D recovered to 22% by 22 June 2017.

Though shifts in the timing, intensity and length of fire seasons have been reported and are expected in future (Flannigan et al., 2016; Jolly et al., 2015), attribution of this particular fire event to changing climate conditions is difficult (but see e.g., Fischer & Knutti, 2015) However, we can quantify the extreme nature

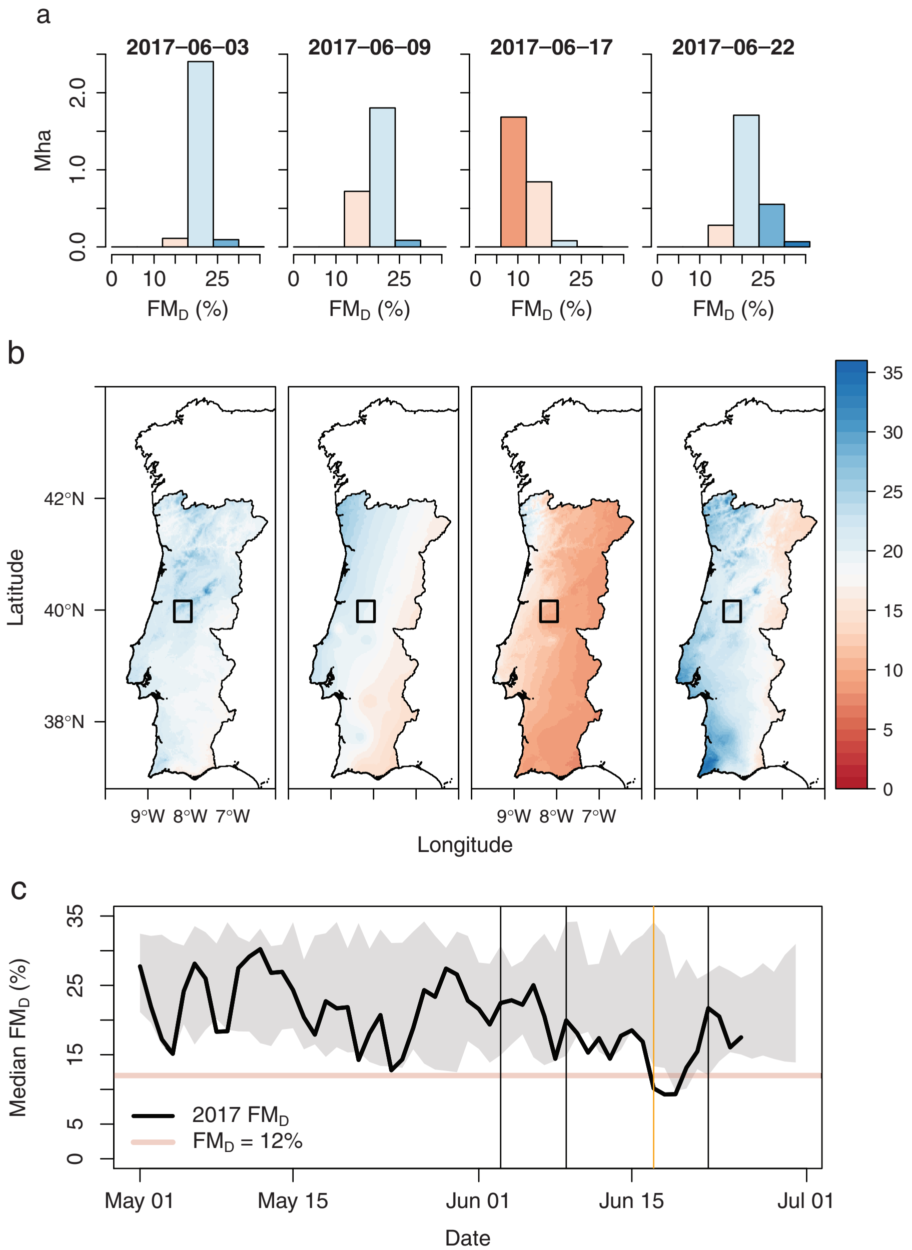

Figure 3. Spatiotemporal patterns of predicted fine dead fuel moisture content (FM_D) in Portugal. (a) Distributions of the Portuguese forest area over six FM_D categories on 3, 9, 17 and 22 June 2017. (b) Spatial patterns of FM_D (%) on 3, 9, 17 and 22 June 2017, with the area affected by the Pedrogão Grande fires indicated by the black rectangle. (c) Time series of the median FM_D in the Pedrogão Grande area in May to June 2017 (black continuous curve) with the historical 5%–95% FM_D range (gray shading), the 12% threshold FM_D for extreme forest flammability (horizontal red line), the start date of the fires on 17 June 2017 (vertical orange line), and the dates of 3, 9, and 22 June 2017 (vertical black lines).

of the fuel moisture conditions in the Pedrogão Grande area at the time of the fires. Since 2000, events of three or more days of median FM_D below the 12% threshold have occurred only three times in the area (30 July to 9 August 2003, 4–7 August 2005 and 7–9 August 2016), but never as early as June. The Pedrogão Grande fires of June 2017 occurred well ahead of the main forest fire season; over the 2001–2015 period covered by our fire history data, 90% of the BA in mainland Portugal has occurred after Julian day 202 (i.e., 21 July). Our analysis of historical fire and weather records (Figure 2) indicates that increases in the frequency of extreme fuel dryness events are highly likely to cause a proportional increase in the area burnt by forest fires, regardless of the time of year.

4. Toward an Early Warning System

We now know that dynamic transformations of forest flammability occur at similar fuel moisture thresholds in disparate forest types in Portugal and Australia (Nolan et al., 2016b). This knowledge, together with a physically based, broadly applicable, model for the prediction of fine dead fuel moisture content from standard weather observations (Resco de Dios et al., 2015), opens the way for near-real time monitoring of forest flammability at national or subcontinental scales (Nolan et al., 2016a). The same model can be driven by medium range weather forecasts, to forecast spatially explicit probabilities for the exceedance of critical forest flammability levels with lead times of 1–2 weeks. Spatially explicit early warning of forest flammability levels at moderate spatial resolutions (e.g., 1–5 km) are achievable with readily available weather records and forecasts; this information would support fire management agencies in preparing and coordinating risk mitigation measures and raise awareness of extreme fire danger among affected communities. Development and implementation of such an early warning capability is particularly significant in the context of projected increases in the frequency of extreme weather events and related shifts in the timing of fire seasons (Bowman et al., 2017; Fischer et al., 2013).

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